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Angular distribution of the neutrons from the reaction Li^7 (p, n) Be^7

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With 5 figures in the text

ABSTRACT

Distributions were measured at four proton energies between 2.7 and 3.5 MeV, at angles up to 150°, using a time-of-flight technique with photographic recording of oscilloscope tracks. The energy of the cyclotron-accelerated protons was varied by degrader foils. The detector efficiency was calibrated with the help of the $T\,(p, n)\,He^3$ reaction. Some comments on the energy precision are made in an appendix.

Introduction

The $Li^7(p, n)Be^7$ reaction is extensively used as a neutron source because of its high yield and the fairly simple target preparation. For that reason it is of some practical interest to know the differential cross-section as a function of angle and proton energy. In the energy interval between threshold ($E_p = 1.88$ MeV) and $E_p =$ 2.55 MeV, absolute angular distributions were measured by Taschek and Hemmendinger [1] in 1948. It was then not yet known that two neutron groups are emitted above $E_p = 2.38$ MeV, one group corresponding to the ground state of Be^7, the other (which is weaker) to the first excited state. Later, some measurements of the intensity ratio between the groups were made at several neutron energies and a few angles [2, 3]. Batchelor and Morrison [4] have investigated the angular distributions of both the groups at $E_p = 2.58$ to 2.88 MeV, using a He^3 proportional counter. Bevington *et al.* [5] have used the time-of-flight method (including time-to-pulse-height converter and multi-channel analyzer) to study the reaction at $2.6 < E_p < 4.2$ MeV. The present work covers the region $2.7 < E_p < 3.5$ MeV as far as the main neutron group is concerned; the weak group could be investigated in the whole angle interval only at 3.5 MeV.

Experimental arrangement

The experimental arrangement has been described in a previous paper [6]. Here will be given a more detailed description of the photometric procedure and of some arrangements made after the publication of that paper. The 80 cm cyclotron at the Nobel Institute was used to accelerate H_2^+ ions to an energy corresponding to 3.5 MeV per proton. The extracted beam was focussed onto a target about 8 m from the cyclotron, arriving there as short ion bursts with a time interval of 82.0 ns. Part of the beam hit a scintillation detector, the signals from which were fed to the vertical deflection plates and an intensity modulation device of a Tektronix 517 oscilloscope. The neutrons (and γ-rays) produced at the target were detected by a plastic scintillator coupled to an RCA 6810 photomultiplier. (The introduction of this 14-stage tube instead of the previously used 10-stage 6342 greatly reduced the needed amount of broadband amplification, and consequently also the troubles due to r.f. disturbances). The pulses from this detector triggered the oscilloscope sweep, thus defining the time of arrival of the neutrons. The position of the beam pulse lines on the screen was then a measure of the flight time. A still camera viewed the screen and the resulting time spectrum was analyzed in a recording photometer. The neutron detector was situated in a collimator (lead and boron-loaded paraffin) that was movable round the target. The target to detector distance could be varied between 1 and 3.5 m, its value at a given angle being chosen in such a way that different peaks would not mix up with each other (since the neutron flight time generally is greater than 82 ns, this might very well happen if no precautions were taken). In the nose of the collimator a lead absorber, 7 mm thick, was placed to attenuate the γ peak to a moderate value. (About 10 % of the neutrons were scattered out by the absorber, while the γ attenuation was about 70 %.)

The lithium target

The target was made by vacuum evaporation of metallic Li onto a tantalum backing, 0.2 mm thick and 35 mm in diameter. The lithium layer had a diameter of 26 mm, while the beam spot was about 20 mm high and 10 mm wide. The backing was supported by an Al plate, 3 mm thick, that formed the end of the beam tube and was cooled by compressed air (Fig. 1). Unfortunately, this Al plate was sufficiently thick to cause a considerable (up to 30 %) attenuation of the neutron flux between 70° and 90° lab. angle. Since the correction for the scattering-out was quite uncertain, the measurements at the angles in question were omitted. The target was transported *in vacuo* from the evaporation chamber to its place at the end of the beam tube, where pumping was immediately begun. The time of exposure to air moisture was thus reduced to about ten seconds, so the conversion to hydroxide (that might jeopardize the stability of the lithium layer and unnecessarily increase the target thickness) was negligible.

Monitoring of the beam

The GM counter used as a monitor was sufficient as long as the proton energy was kept constant, but since the measurements were to comparise several proton energies, a beam current integrator had to be used as a complement. The integrator was of the same type as that described in [7], having a condenser and a glow lamp as its main components.

As a rule, it is not quite ideal to use a γ-counting device such as a GM tube as a monitor for neutron-producing reactions. However, in the bombardment of Li with protons, the γ yield from $Li^7(p, n'\gamma)Be^7$ and $Li^7(p, p'\gamma)Li^7$ greatly preponderates over that from Coulomb excitation in the backing, especially when the lowest energies are suppressed by a lead shield. So in that case a GM monitor works quite well, but in the reaction $T(p, n)He^3$ (used for the calibration of the detector efficiency) the

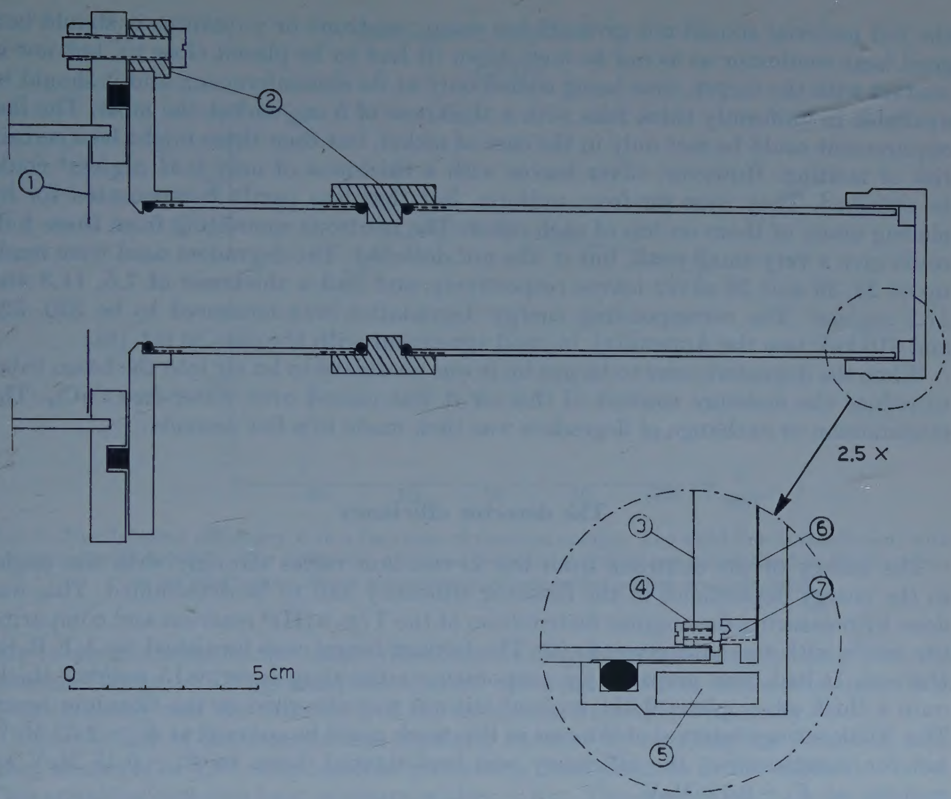

Fig. 1. Target arrangement. 1, tantalum diaphragm; 2, plexiglass insulators; 3, beam energy degrader with (4) holder; 5, mantle for cooling water (not used in the present experiments); 6, target; 7, target clamp. Black areas are rubber gaskets.

γ-yield from tritium is extremely small; the monitor then only serves as a check on the integrator.

The counting rate ratio between the GM monitor and the integrator varied by 5 % (unless otherwise stated, all empirical errors given in this paper refer to the standard variation in a single measurement). The corresponding figure for the detector-to-monitor ratio (with the background subtracted) was 2.5 %. The contribution from counting statistics was always less than 1 %. The comparison between neutron intensities at different proton energies could be done with an accuracy of 1–2 % since mean values of the monitor-to-integrator ratio could be used.

By checking the validity of the inverse square law when the target to detector distance was varied, it was shown that the monitor counting rate was not influenced by the position of the collimator.

Energy variation of the protons

Since the frequency of the cyclotron could not be changed, the beam energy could only be varied by inserting energy degrading foils. To be suitable for the purpose, the foil material should not give off too many neutrons or γ-quanta, it should be a good heat conductor so as not to melt down (it had to be placed close to, but not in contact with the target, thus being cooled only at its circumference), and it should be available in uniformly thick foils with a thickness of 5 mg/cm² at the most. The last requirement could be met only in the case of nickel, but then there might be a certain risk of melting. However, silver leaves with a thickness of only 0.31 mg/cm² could be obtained. They were far from uniform, but that was partly compensated for by placing many of them on top of each other. The neutrons emanating from these foils could give a very small peak, but it was not detected. The degraders used were made up of 24, 36 and 56 silver leaves respectively, and had a thickness of 7.5, 11.3 and 17.2 mg/cm². The corresponding energy degradation was measured to be 330, 520 and 810 keV (see the Appendix), in good agreement with the data in ref. [8].

When the degraders were to be put in, it was necessary to let air into the beam tube; to reduce the moisture content of this air it was passed over water-free $CaCl_2$. The introduction or exchange of degraders was then made in a few seconds.

The detector efficiency

The energy of the neutrons from the Li reaction varies strongly with the angle, so the energy dependence of the detector efficiency had to be determined. This was done by measuring the angular distribution of the $T(p, n)He^3$ reaction and comparing the result with the data given in [9]. The tritium target was furnished by A.E.R.E., Harwell. It had been prepared by evaporating a titanium layer, 0.15 mg/cm² thick, onto a thick silver plate. 0.011 mg/cm² tritium was absorbed in the titanium layer. The whole energy interval of interest in this work could be covered at $E_p = 3.53$ MeV, but for completeness, the efficiency was investigated down to $E_n = 0.45$ MeV by running at $E_p = 2.72$ MeV.

If multiple scattering and the effect of carbon nuclei are neglected, as well as the pulse height spread in the photomultiplier, the theoretical efficiency should be

$$\eta = \{1 - \exp(-\mu t)\}(1 - B/E_n)$$

where E_n is the neutron energy, B the neutron energy that corresponds to the discriminator threshold, t the scintillator thickness, and

$$\mu = \sigma N \varrho \cdot x/(12 + x)$$

where N is Avogadro's number, ϱ the density of the scintillator and $x/(12+x)$ its weight fraction of hydrogen, corresponding to the gross formula CH_x. σ is the cross section for elastic scattering of neutrons by protons.

The experimental values (see Fig. 2) have been multiplied by 1.12 to correct for the absorption in the lead absorber (being about 11 % except for two narrow resonances at 0.54 and 0.71 MeV, where it rises to about 18 %; the corresponding angles were always avoided) and then normalized to fit the theoretical curve at its maximum point by multiplying with another factor of 1.27. A B-value of 0.4 MeV was inferred from the experiments, and this figure was used when drawing the theoretical curve. Taking into consideration the simplifying assumptions the agreement between theory and experiment is remarkably good. The discrepancy of the absolute values may be

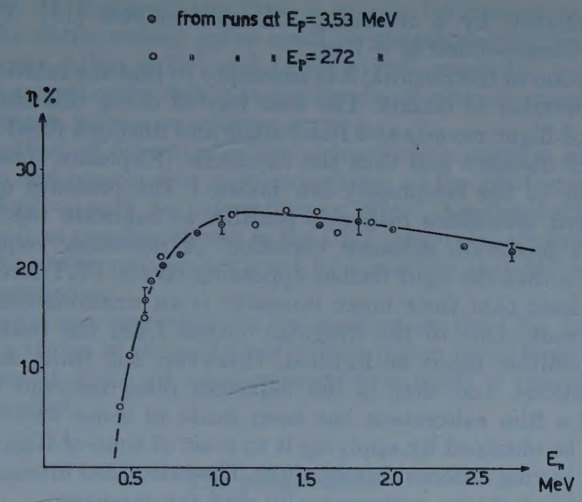

Fig. 2. The detector efficiency η as a function of neutron energy. The solid line is theoretical with a bias value of 400 keV. The ordinates of the experimental points are normalized to fit the curve at its maximum. Some representative estimated errors are indicated.

due to uncertainties in the target thickness. It may be noted that neutrons from the reaction $Ti^{49}(p, n)V^{49}$ (ground state) were observed in these calibration runs, but their intensity was less than 10 % of the minimum $T(p, n)He^3$ intensity.

The stability of the detector was regularly checked by counting the 70 keV X-rays from a sample of Tl^{204} that could be put into a fixed position in the collimator tube. This counting rate was kept constant within ± 6 %. This was shown to be equivalent to ± 3 % in the amplification, which would correspond to a bias uncertainty $dB = \pm 12$ keV, if the scintillation response were proportional to the recoil proton energy. Because of quenching effects, this is not the case, the response more closely being proportional to the range of the protons (see e.g. [10]). However, this will reduce dB by less than 20 %. The theoretical efficiency formula then gives a spread in efficiency $d\eta/\eta = \pm dB/(E_n - E_0)$, where $E_0 = 400$ keV. The lowest energy for which intensity measurements on the Li reaction were made was about $E_n = 550$ keV, so the spread was always less than ± 8 %.

The background, nearly all of which being due to dark current, varied between 35 and 45 counts/s. It was checked that it was independent of the position of the detector, indicating that also the amplification of the photomultiplier was independent of position (the various magnetic stray fields and the geomagnetic field might have been sufficient to give a noticable dependence).

Evaluation of the photometer records

The total number of oscilloscope sweeps in a run was registered by a scaler. Thus only the relative distribution between different particle groups had to be evaluated from the photographs. These were taken by an oscilloscope camera, using Ilford 5B52 35 mm film. In order to reduce errors caused by differences in the development, all exposures (including the film calibration) were made on the same film strip. The records were analyzed by a recording microphotometer [11]. The width of the illuminating slit corresponded to ~ 2 ns.

For the evaluation of the records, it is necessary to find the relationship connecting blackening and number of counts. The best way of doing this should be to take a number of time-of-flight records at a fixed angle and during a fixed time, varying the target to detector distance and thus the exposure. (Exposure time variation is not expedient because of the reciprocity law failure.) The presence of several particle groups of different intensities makes it possible to calibrate the film over a wide range by only a moderate distance variation. A necessary requirement for this method to work is that the light flashes appearing on the CRT screen have constant intensity, or at least that their mean intensity is an unambiguous function of the mean beam current. Due to the irregular output from the beam scintillator not even the last condition could be fulfilled. However, one thing is uninfluenced by intensity fluctuations, and that is the exposure ratio between different particle groups. Thus, if a film calibration has been made in some way, a criterion of its correctness may be obtained by applying it to a set of time-of-flight records made at a fixed angle but having different blackenings. The calculated intensity ratios between the groups should not change systematically with the exposure.

An attempt was made to obtain a characteristic curve by displaying delayed trigger pulses on their own sweeps, replacing the target radiation by a radioactive sample. The exposure time was kept constant and the sample distance was varied. However, the result did not fulfil the above-mentioned criterion, probably due to the slimness of the peaks obtained in this manner — 1 ns compared to 5 ns for peaks obtained in cyclotron runs (the light spot width of the photometer was accordingly reduced in these experiments).

A semi-empirical approach to the problem was then made by applying the Silberstein [12] formula to a set of fixed-angle, time-of-flight runs. *A priori*, there is little reason to hope that this formula would hold in a case like this (it finds application mainly for ionizing radiation exposures [13]); however, it turned out to work quite well, except at small exposures. The formula says that $D = \log I_0/I = C \cdot \log (1 + \alpha E)$, where D is the photographic density, E the exposure, and α and C are constants. I is the photometer deflexion and I_0 the deflexion that corresponds to unexposed film. For large exposures ($\alpha E \gg 1$), $D \sim \text{const} + C \cdot \log E$, representing the linear part of the characteristic (D vs $\log E$) curve.

To use the formula, $\log \{(I_0/I)^{1/C} - 1\} = \log (\alpha E)$ was plotted against $\log \{(I_0/I) - 1\}$. The exposure can be written $E = n \cdot \bar{J}$, where n is equivalent to the number of counts per channel, and $\bar{J}$ is the mean light intensity of the CRT flashes. The C-value had to be found by trial and error, the criterion of a correct value being the above-mentioned freedom from systematic variations. $C = 1.3 \pm 0.1$ turned out to give good results in the whole region $0.2 < D < 1.5$. (This corresponds to a gradation of about 1.15, a very reasonable value.) The fluctuations in peak height ratio were of the order of 5–10 % for ratios between 5 and 20; better results are probably not to be expected from photographic records (cf. [13]). Below $D = 0.2$, the Silberstein formula failed, but the demand for constancy of intensity ratios made it possible to make the necessary correction. Higher densities than $D = 1.5$ were never used.

It should be noted that the freedom from systematic variations is a necessary but not sufficient condition for the calibration to be correct. In fact, if the scale of the log E axis were changed (which corresponds to putting $E^p (p + 1)$ instead of E), this freedom would be retained, but all calculated intensity ratios would change in a systematic manner. If, however, one ratio is known beforehand, p could be determined and thus the characteristic curve could be unambiguously ascertained. In the present case, for the $\mathrm{Li}^7(p, n)\mathrm{Be}^7$ and $\mathrm{Li}^7(p, n)\mathrm{Be}^{7*}$ reactions, $p = 1$ gave a ratio $\sigma(0^\circ)/\sigma^*(0^\circ)$ that agreed quite well with the results of previous measurements [2, 3], so there was no reason to choose another p-value.

This indirect method of determining the characteristic curve is certainly far from ideal. However, in one respect it is quite satisfying: all the photographic aberrations that could interfere — such as intermittency effect, Eberhard effect and tanning effect [14] — as well as possible effects in the CRT screen [15] are included in the calibration. This could not have been achieved by a method that did not use the time-of-flight peaks themselves.

The light intensity was dependent on the position on the CRT screen, but it was quite constant in a region in the middle of it, this region being large enough to cover a full cyclotron period. Since all measurements were made in this region, no corrections had to be applied.

The peak widths

(a) Without degrading foils

Contrary to the multi-channel analyzer case, the shape of the peaks has to be investigated when a non-counting device such as the present one is used. It would, of course, be very laborious to convert the peaks in all runs to their corresponding linear representation, so this was done only in a few cases. It then turned out that the true areas of both neutron and gamma peaks were about 15 % larger than $h \cdot \Gamma$, where h is the height and Γ the half-width of the peak. The gamma peaks were almost symmetric, resembling a Gaussian distribution, but somewhat broader at the base, while the neutron peaks had a bigger tail comprising about 10 % of their area. The neutron peaks were also considerably broader ($\Gamma_n = 5.8$ ns) than the gamma peaks ($\Gamma_\gamma = 4.5$ ns), their width being remarkably independent of neutron energy and flight distance. The fact that the half-widths were also independent of blackening is a good support for the film calibration. The standard error in Γ was 6 %, a value that agrees well with the uncertainties in the reading of the photometer records.

There are a great many reasons that may explain the difference between Γ_n and Γ_γ, such as (1) beam energy spread, (2) target thickness, (3) angular spread (due to beam focussing and the finite size of the detector), (4) scattering in the collimator tube, (5) detector thickness, and furthermore the difference between electron- and proton-induced scintillations as regards (6) decay time, (7) pulse height distribution and (8) maximum pulse height. On the other hand, the constancy of Γ_n indicates that the combined effects of (1), (2), (3) and (5) must be quite small (this statement is confirmed by calculations). As regards (4), later experiments with a tapered collimator (that should considerably reduce the number of scattered-in neutrons) shows that it gives no measurable contribution to Γ_n. The decay-time difference (6) is reported to be very small for plastifluors [16]. Point (8) is excluded by the fact that 300 keV electrons (maximum Compton electron energy of the gammas from lithium) give the same pulse height as 1.3 MeV protons (this statement holds for the plastifluor NE 102 [17], but Pilot "B" is said to be of a very similar composition).

Calculations based on the photomultiplier pulse shape [18] and on pulse height spectra computed from recoil proton and Compton electron energy distributions, have

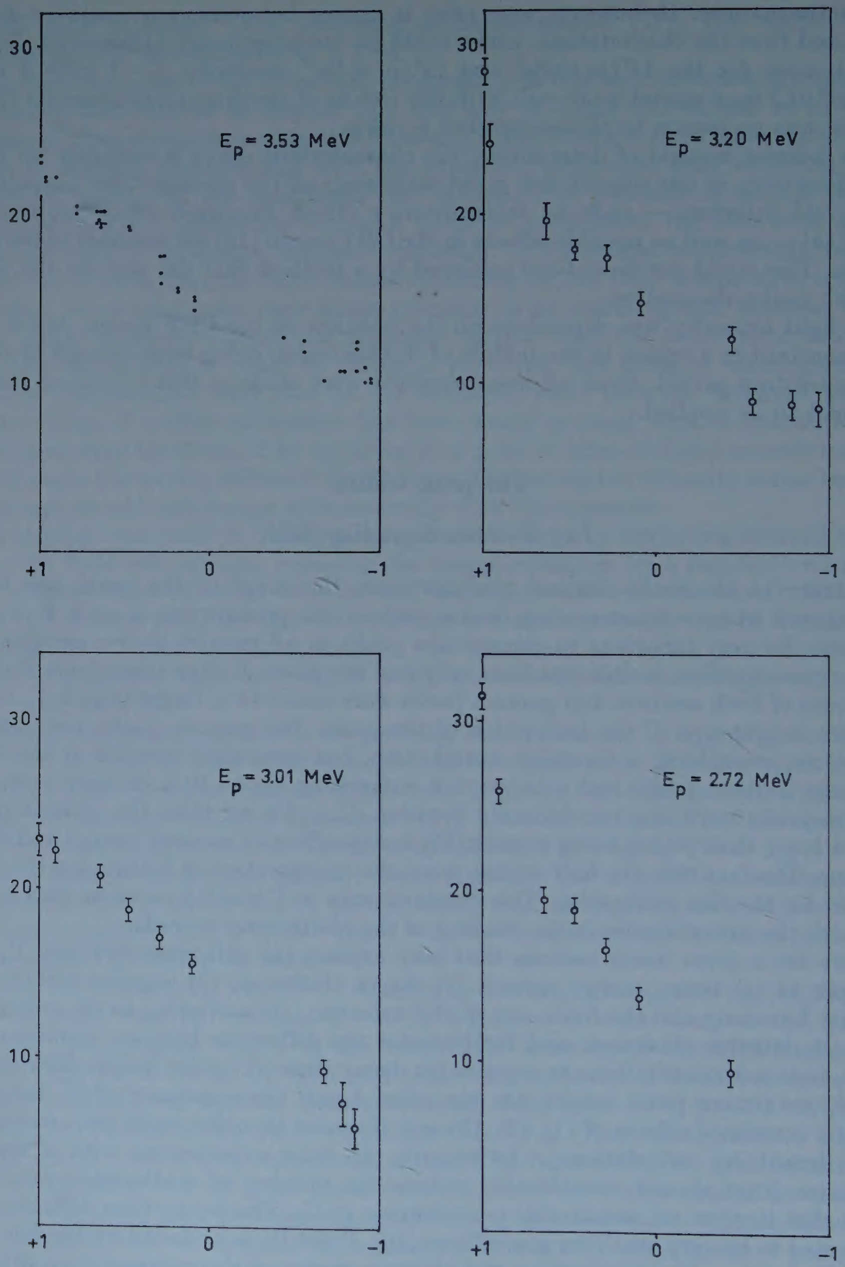

Fig. 3. Angular distributions for the reaction $Li^7 (p, n) Be^7$. Centre-of-mass cross-sections in mb/std plotted against cos $\theta_{c.m.}$. The scattered points in the 3.53 MeV diagram represent all individual measurements made. (To avoid confusion, their abscissas have sometimes been a little displaced.) The other diagrams give estimated errors.

failed to indicate a sufficiently large difference in time spread. With the reservation that such calculations are somewhat uncertain, this rules out (7), and so the problem has to be left unsolved.

There was no significant correlation between peak height ratio and peak width ratio, so the width could be regarded as a constant when calculating the peak areas.

(b) With degrading foils

The attenuators should cause an energy straggling of the protons amounting to about 95 keV, and an angular spread of about 10° (both half-widths referring to the thickest one). The straggling was calculated in accordance with Livingston and Bethe [19], giving 63.4 as the "effective" Z-value of silver; for the multiple scattering Molière's formulas [20] were used. The calculation of the neutron energy distribution that is caused by the proton scattering, involves complicated solid geometry, but, since the scattering angles were small, a simple approximation could be used for $40° < \theta < 140°$. For smaller and larger angles the scattering contribution to the neutron energy spread is quite small. Good agreement between theoretical and empirical results was obtained if the straggling contribution was increased by $\sim 20\%$. That increment might be due to the non-uniformity of the silver leaves. The half-widths measured in these runs ranged between 6 and 15 ns.

Procedure and results

The experiments were performed at 3.53, 3.20, 3.01 and 2.72 MeV proton energy (the energy determination is treated in the Appendix). The beam current was kept between 1 and 2.5 μA (since H_2^+ ions were accelerated, this corresponds to between 2 and 5 μA proton current). 30,000–50,000 counts were recorded in each run, this rather high number being necessary to get a suitable blackening of the film. The statistical fluctuations were thus kept at a level that was neglibibly low compared to other errors. The time required for one run ranged from 0.5 to 3 minutes. In order to reduce systematic errors in the distributions, the angle settings were in principle made in the following order: 0°, 20° ... 140°, 150°, 130° ... 30°, 10° (at the lower energies the angle intervals were sometimes greater, but the principle was retained).

The normalization of the cross-sections was made by putting the sum of the intensities of the two groups at 0°, $E_p = 3.53$ MeV, equal to 38 mb/std (lab. system). This figure was derived from Taschek and Hemmendinger's [1] absolute cross-section at the 2.3 MeV resonance peak, together with the relative intensities measured by Marion, Bonner, and Cook [21] from threshold up to 4 MeV.

Complete angular distributions for both groups could be measured only at $E_p = 3.53$ MeV, since the peak broadening due to the attenuators became too serious at backward angles. At $E_p = 2.72$ MeV, the weak group could not be investigated at all. The results are shown in Figs. 3 and 4. All measurements at $E_p = 3.53$ MeV are included in the diagrams in order to show the magnitude of the random errors. They are smaller for the main group, which is quite natural since this comprises from 70 % of the total counts at 0°, down to 40 % at 150°, while the corresponding figures for the second group are 8 % and 5 %, implying a higher sensitivity to photographical errors. The previously mentioned uncertainty in the C-value (± 0.1) was found to correspond to less than $\mp 4\%$ in the main group intensity, and to less than $\pm 7\%$

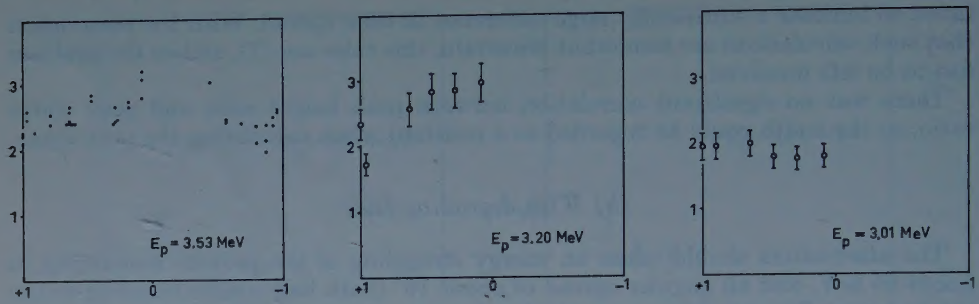

Fig. 4. Angular distributions for the reaction $Li^7(p, n)Be^{7*}$. The same representation as in Fig. 3.

in the intensity of the second group. The fluctuations in the detector efficiency contributes to the errors only at the largest angles.

At the lower proton energies as a rule only one run was made at each angle. For this reason the corresponding diagrams present estimated errors.

Discussion of the results and the method

When these measurements were performed, no angular distributions for the reaction had been published for proton energies greater than 2.9 MeV. It was expected that a test of the method could be achieved by degrading the cyclotron energy down to the region (2.58–2.88 MeV) where cross-sections had been measured by Batchelor and Morrison [4]. Unfortunately, this proved to be impracticable because of the large spread at low energies. The results of Bevington *et al.* [5], however, covering the region $2.6 < E_p < 4.2$ MeV, are easy to compare with the most reliable of the present angular distributions, viz. the one at $E_p = 3.53$ MeV. It then turns out that the agreement is very good as regards the main neutron group. For the weak group, however, it is quite poor, their cross-section rising almost linearly (in a $\sigma_{c.m.}$ vs. $\cos\theta_{c.m.}$ diagram) from 2.6 mb/std at 0° to 4.6 mb/std at 180°, while the present work indicates a nearly constant cross section of 2.5 mb/std. Supposing their distribution to be correct, the erroneousness in the present results could originate either in a faulty calibration of the detector efficiency, or in a faulty characteristic curve of the film. The first alternative can be excluded for the following reason: to get agreement the efficiency must be strongly decreased at low energies. That would mean an increase in the cross-section of the main group at backward angles amounting to $\sim 40\,\%$ at 150°, and thus a destruction of the agreement for the main group. From the theoretical point of view, a higher efficiency at low energies could be possible (taking into account multiple scattering), but not a lower.

As regards the film calibration, it should be pointed out that the intensity ratio between the weak and the strong neutron groups as measured on the photometer records did not change very much with the angle (it was $\sim 10\,\%$ at 0°, went through a maximum of $\sim 20\,\%$ and then decreased to $\sim 15\,\%$ at 150°). Since the ratio is correct at 0°, it thus looks quite improbable that it should be so drastically wrong at 150°. The main difference between runs at these extreme angles is that the relative background is much higher in the backward directions. It does not seem possible, however, to construct a characteristic curve that leads to agreement for the weak group, without destroying the inner consistency of the present results as regards independence of exposure and constancy of gamma peak half widths.

As regards the distributions at lower energies, the pattern is quite similar: agreement within the stated errors for the main group and also for the weak group at small angles, while at $\theta_{\mathrm{c.m.}} = 90°$ the present weak group cross-sections are 20–30 % lower than those of Bevington *et al.*

The time-of-flight system used for these measurements was developed before we had got a time-to-pulse-height converter and kick-sorter. The chief advantages of the system are that it is relatively cheap and uncomplicated. The absence of discrete channels makes the determination of peak positions very accurate, and thus also the correction for time-scale non-linearity. There are no troubles with end effects caused by overlapping of start and stop pulses as in a time-to-pulse-height converter. Quite large variations in stop-pulse amplitude may be tolerated without noticeable peak broadening, since these pulses can easily be transformed in the way illustrated by Fig. 3 in ref. [6].

The main disadvantage is obviously the uncertainties in the intensity measurements. If the variations in pulse amplitude of the beam scintillator could be eliminated, the film calibration could be made in a direct and more reliable manner. Attempts have been made to achieve this by having the beam scintillator pulses to control the phase of an oscillator, the output of which was fed to the oscilloscope. However, the pulse amplitude fluctuations caused a considerable time spread, the gamma peak half-widths being 8–9 ns.

There is certainly one radical way of solving the intensity problem, and that is to turn back to the moving film method. By covering the CRT screen with black paper except for a narrow horizontal slit, every detector event would be represented by a dot for each cyclotron period. The film could then be read out by an automatic arrangement of the same type as that constructed by Hunt *et al.* [22]. They got an intrinsic half-width of 0.3 mm, which would mean 3 ns if applied to our film records and thus be quite sufficient.

That method and the one used in the present work would be complementary to each other in a very good way.

APPENDIX

Some observations concerning the time measurements

Since the cross-sections of the reactions studied here changed very slowly with proton energy, there was no need for high accuracy in the energy determination. In other applications, however, accuracy is imperative, and for that reason a study was made of the precision attainable in the time measurements.

A series of runs made for film calibration purposes, proved to be suitable for an accurate determination of the proton energy. In this series, the angle was kept constant at 25°, and the distance was varied from 194 cm up to 349 cm. The neutron velocity could then be measured without the uncertainty caused by the difference in trigger delay between neutrons and gamma quanta. The resulting value of the proton energy, 3.53 ± 0.01 MeV, was somewhat higher than that reported in [6]; this was certainly due to some geometrical adjustments in the cyclotron made in the meantime. Using the well-known Q-value of the $\mathrm{Li}^7(p,n)\mathrm{Be}^7$ reaction (-1.646

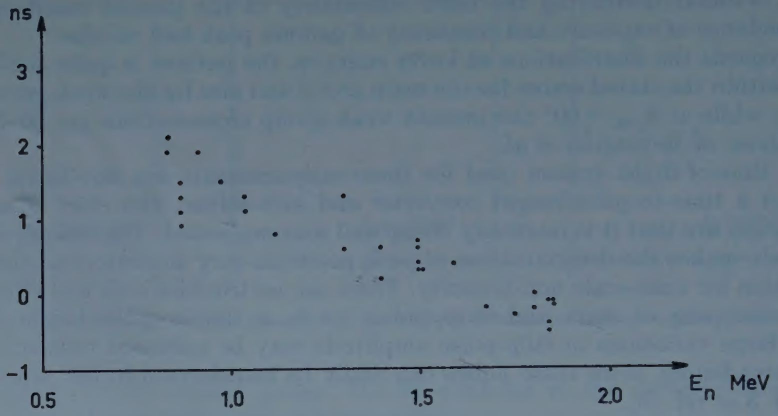

Fig. 5. Trigger delay as a function of neutron energy.

MeV), neutron flight-times were calculated for the angles and distances used in the angular distribution measurements. Comparison of the theoretical and experimental values then gave the variation in trigger delay with neutron energy (Fig. 5). The figure also shows that the spread in time measurements as a rule is less than 0.3 ns.

The fact that time corrections of this type must be applied is a result of the comparatively long rise time (~ 8 ns) of the photomultiplier pulses. The corrections would be much smaller if a single-channel analyzer were used instead of a discriminator for the gating of the pulses, but then the detector efficiency would be smaller and the efficiency curve would have a sharper maximum (cf. [23]).

It is to be noted that the position of the "zero correction" line in Fig. 5 depends, of course, on the energy of the gammas used as time reference. Thus, gamma rays from aluminum bombarded with 3.5 MeV protons gave a peak ~ 1.7 ns earlier than the gammas from the lithium target. According to Gattner and Selove [17], one would expect the time correction to be zero for $E_n \sim 1.3$ MeV (cf. the peak shape discussion). The deviation might be due to the difference between electron and proton energy distributions.

Further development of photomultipliers or the introduction of an automatic gain control amplifier such as that designed by Johansson [24], will greatly reduce the corrections now discussed and, of course, also the half-widths attainable.

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